

COMETARY EVOLUTION: CLUES ON PHYSICAL PROPERTIES FROM
CHONDRITIC INTERPLANETARY DUST PARTICLES

Frans J. M. Rietmeijer
Department of Geology
University of New Mexico
Albuquerque, New Mexico

Ian D. R. Mackinnon
Electron Microscope Centre
University of Queensland
St. Lucia, QLD 4067, Australia

COMETARY EVOLUTION: CLUES ON PHYSICAL PROPERTIES FROM CHONDRITIC INTERPLANETARY DUST PARTICLES. (*)

Frans J. M. Rietmeijer,

Department of Geology, University of New Mexico, Albuquerque, NM 87131, USA

and

Ian D. R. Mackinnon,

Electron Microscope Centre, University of Queensland, St. Lucia, QLD 4067, Australia.

INTRODUCTION.

The degree of diversity or similarity detected in comets depends primarily on the lifetimes of the individual cometary nuclei at the time of analysis. It is inherent in our understanding of cometary orbital dynamics [Weissman, 1985] and the seminal model of comet origins by Oort [Oort, 1950] that *cometary evolution* is the natural order of events in our Solar System. Thus, predictions of cometary behaviour in terms of bulk physical, mineralogical or chemical parameters should contain an appreciation of temporal variation(s). Previously, Rietmeijer and Mackinnon [1987] developed mineralogical bases for the chemical evolution of cometary nuclei primarily with regard to the predominantly silicate fraction of comet nuclei. We suggested that alteration of solids in cometary nuclei should be expected and that indications of likely reactants and products can be derived from judicious comparison with terrestrial diagenetic environments which include hydrocryogenic and low-temperature aqueous alterations. In a further development of this concept, Rietmeijer [1988] provides indirect evidence for the formation of sulfides and oxides in comet nuclei. Furthermore, Rietmeijer [1988] noted that timescales for hydrocryogenic and low-temperature reactions involving liquid water are probably adequate for relatively mature comets, e.g. P/comet Halley.

In this paper, we will address the evolution of comet nuclei physical parameters such as solid particle grain size, porosity and density. In natural environments, chemical evolution (e.g. mineral reactions) is often accompanied by changes in physical properties. These concurrent changes are well-documented in the terrestrial geological literature, especially in studies of sediment diagenesis [Berner, 1980] and we suggest that similar basic principles apply within the upper few meters of active comet nuclei.

The database for prediction of comet nuclei physical parameters is, in principle, the same as used for the proposition of chemical evolution [Rietmeijer and Mackinnon, 1987]. We use detailed mineralogical studies of chondritic interplanetary dust particles (IDPs) as a guide to the likely constitution of mature comets traversing the inner Solar System. While there is, as yet, no direct proof that a specific sub-group or type of chondritic IDP is derived from a specific comet [Mackinnon and Rietmeijer, 1987], it is clear that these particles are extraterrestrial in origin [Bradley *et al.*, 1988] and that a certain portion of the interplanetary flux received by the Earth is cometary in origin [Brownlee, 1985]. Two chondritic porous (CP) IDPs, sample numbers W7010A2 and W7029C1, from the Johnson Space Center Cosmic Dust Collection have been selected for this study of putative cometary physical parameters. This particular type of particle is considered a likely candidate for a cometary origin [Bradley *et al.*, 1988] on the basis of mineralogy, bulk composition and morphology. While many IDPs have been subjected to intensive study over the past decade, we can develop a physical parameter model on only these two CP IDPs because few others have been studied in sufficient detail [Mackinnon and Rietmeijer, 1987].

OBSERVATIONS.

The data used in this analysis have been obtained solely from Analytical Electron Microscope studies of individual CP IDPs W7010A2 and W7029C1. The latter IDP was provided in two separate allocations W7029A23 and W7029A24 by the JSC Curatorial Facility. In each case the majority of grains within each allocation has been examined for mineral identity (i.e. structure and composition determinations) and grain size and shape. The dimensions of typically platy grains in both IDPs have been measured from transmission electron micrographs (with a precision of ~1%) and calculated as the root-mean-square (rms) grain size. This size is calculated by the relation $(a^2+b^2)^{1/2}$ where a and b are two orthogonal dimensions across a grain.

Further details on individual mineral analyses and abundances, as well as their interpretations, are given in Mackinnon and Rietmeijer [1984, 1987], Rietmeijer and Mackinnon [1985a] and Rietmeijer [1989]. For simplicity, not all grains within each IDP are utilised in this study. Only non-carbonaceous grains and grains which are part of the IDP matrix are included in the grain size histograms shown in Figures 1 and 2. Thus, the data for IDP W7010A2 excludes measurements of large ($> 1.0 \mu\text{m}$) euhedral and rod-shaped silicate crystals [Rietmeijer, 1989] while the data for IDP W7029C1 exclude poorly graphitised carbon [PGC] grains which constitute ~45% of all grains in this IDP [Rietmeijer and Mackinnon, 1985a].

The ultrafine platy grains in IDP W7010A2 are embedded in amorphous carbon and, as yet, unidentified hydrocarbons [Bradley, 1988; Rietmeijer, 1989]. The presence of these carbonaceous species suggests a low thermal regime ($< \sim 250^\circ\text{C}$) in the anhydrous IDP parent body(ies) [Rietmeijer, 1986; Rietmeijer and Mackinnon, 1985b]. In the case of IDP W7029C1, the degree of ordering inferred from the PGC basal spacing is consistent with a thermal regime of $\sim 300^\circ\text{C}$ in this IDP [Rietmeijer and Mackinnon, 1985b]. While this IDP is nominally an anhydrous variety, ~11% of all grains are layer silicates and qualitatively, the mineralogy of IDP W7029C1 is similar to that interpreted from the chemical signature of ultrafine-size silicate dust in P/comet Halley [Rietmeijer *et al.*, 1989].

The omission of grain size data for carbonaceous phases, as well as data related to the presence of Ti-rich minerals which have pseudomorphic textures due to a temperature dependant transformation, limits a thorough interpretation of grain size distributions for these two CP IDPs. Nevertheless, the choice of grains for this size distribution comparison implies an analysis of processes which have affected the bulk of the IDP (and, by implication, the IDP parent body(ies)). The size distribution for 254 grains in IDP W7010A2 and for 157 grains in IDP W7029C1 are shown in Figures 1 and 2, respectively.

DISCUSSION.

Interpretations of grain size distributions are, to a first approximation, model dependant and for the sake of discussion, we list below important assumptions for these interpretations:

- (1) chondritic porous IDPs are samples of cometary dust,
- (2) hydrocryogenic and low-temperature aqueous alterations of anhydrous IDPs occurs on comet nuclei,
- (3) the chemical and mineralogical diversity of chondritic IDPs is a good argument for similar diversity in comet nuclei.

While we have argued for mineralogical diversity, and thus evolution, in cometary nuclei [Rietmeijer and Mackinnon, 1987], there is as yet little understanding of the spatial variations of comet mineralogy with time. Nevertheless, if we compare the behaviour of terrestrial sediments during diagenesis, it is apparent that grain size distributions follow well-defined and predictable trends [Berner, 1980]. For example, grain sizes during terrestrial diagenesis generally show initially a strongly peaked size

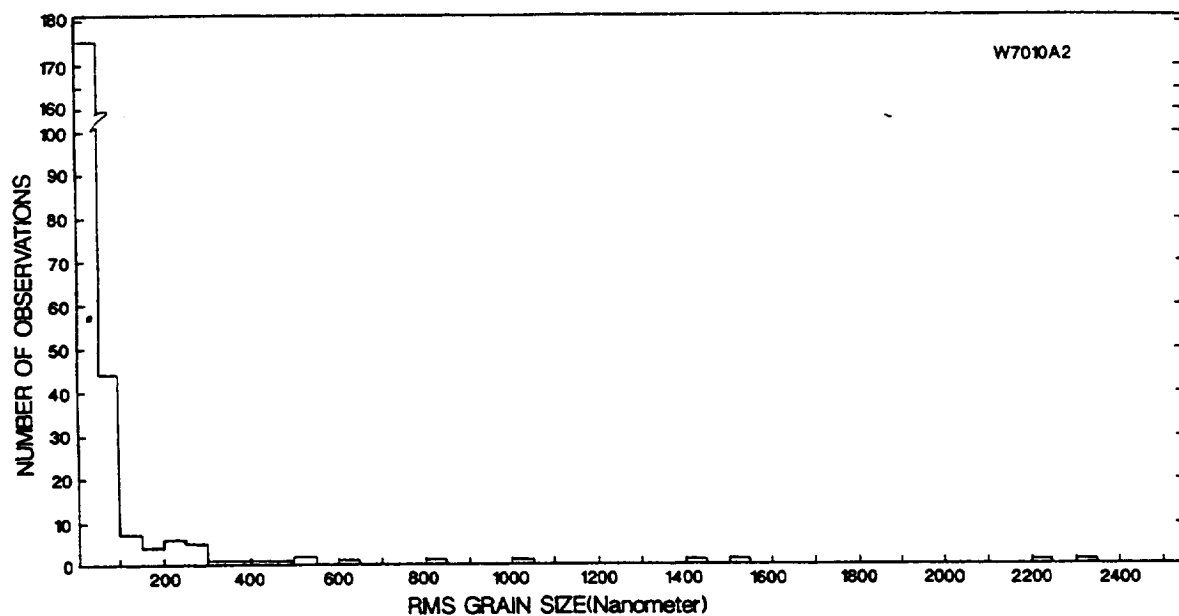


FIGURE 1: Root-mean-square grain size distribution for 254 mineral grains in chondritic porous interplanetary dust particle W7010A2.

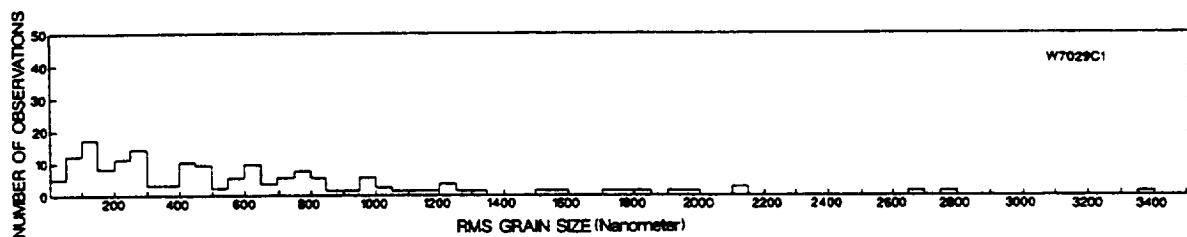


FIGURE 2: Root-mean-square grain size distribution for 157 mineral grains in chondritic porous interplanetary dust particle W7029C1.

distribution in the original sediment which flattens and shifts to a higher mean grain size with further diagenesis. Also a concomittant decrease in porosity accompanies an increase in the median grain size in terrestrial sediments [Berner, 1980].

The rms grain size distribution for IDP W7010A2 [Figure 1] shows a distinct positive skewness which is markedly different from the much flatter distribution for IDP W7029C1 [Figure 2]. Also, the mean rms grain size for each distribution differs, viz. 96.85 nm (W7010A2) and 562.1 nm (W7029C1). These data suggest comparatively advanced diagenesis for IDP W7029C1 relative to IDP W7010A2 and is consistent with the higher thermal regime indicated for the former. Both IDPs are of the chondritic porous subtype. Yet, the moderately higher median grain size for IDP W7029C1 (1325 nm) compared to 1125 nm for IDP W7010A2 indicates a slightly lower porosity for the former and suggests that mineralogical evolution of cometary nuclei will be accompanied by subtle changes in grain size, and consequently also in nucleus porosity and density. Measured densities for chondritic IDPs are between 0.7 and 2.2 g.cm⁻³ [Flynn and Sutton, 1988; van der Stap, 1986]. Unfortunately, the porosity of chondritic IDPs is poorly known but it may be as high as 90% for anhydrous chondritic IDPs and ~70% for a layer silicate-rich IDP [Mackinnon *et al.*, 1987].

Assuming that (1) terrestrial diagenesis can be used to model the chemical, mineralogical and physical evolution of chondritic IDPs and (2) chondritic IDPs are samples of cometary dust, it will be a prerequisite to assess grain size distributions of chondritic IDPs. Comet nucleus models should consider differences in physical properties (grain size, porosity and density) on length-scales of at least ~60 μ m which is the size of the largest chondritic IDP presently collected from the Earth's stratosphere. The extent and spatial variations with time of these differences within cometary nuclei will be different for individual comets and will depend on inherent comet nucleus properties such as ice-dust ratios, the structural state of dust, the evolution of comet orbits and comet lifetime.

CONCLUSIONS.

Petrological analyses of chondritic porous IDPs suggest that grain size, density and porosity of comet nuclei may evolve during their lifetime in the Solar System. Effects of physical evolution, as well as chemical and mineralogical evolutions, in cometary nuclei may be subtle. The extent and spatial variations with time are presently unknown but it seems imperative for models of active short-period comets to consider the possibility of dust evolution.

We believe that Analytical Electron Microscope analyses of chondritic IDPs, in conjunction with astronomical observations and theoretical modelling, will yield the data to model comet nucleus evolution. It seems obvious that putative evolutions of comet nucleus physical properties can place engineering constraints on a Comet Nucleus Sample Return Mission. For example, the mode of penetration (rotation or percussion) selected for a "smart nucleus penetrator" as a function of resistance encountered during descent into the nucleus may critically depend on pre-programmed density differences. Modelling the physical, chemical and mineralogical evolution of cometary dust properties will have a qualitative character until a successful Comet Nucleus Sample Return Mission. However, the possibility of comet nucleus evolution may have important implications for mission planning and the type of sample that will be returned.

REFERENCES.

- Berner, R. A.: Early Diagenesis. A theoretical Approach. Princeton University Press, 1980.
Bradley, J. P.: Analysis of chondritic interplanetary dust thin-sections. *Geochim. Cosmochim. Acta*, vol.

- 52, 1988, pp. 889-900.
- Bradley, J. P.; Sandford, S. A.; and Walker, R. M.: Interplanetary Dust Particles. In: *Meteorites and the Early Solar System* (Kerridge, J. F. and Matthews, M. S., Eds.), University Arizona Press, 1988, pp. 861-898.
- Brownlee, D. E.: Collection of cosmic dust: Past and future. In: *Properties and Interactions of Interplanetary Dust* (Giese, R. H. and Lamy, P., Eds), D. Reidel Publ. Co, Dordrecht, Holland, 1985, pp. 143-147.
- Flynn, G. J.; and Sutton, S. R.: Cosmic dust particle densities inferred from SXRF elemental measurements. *Meteoritics*, vol. 23, 1987, pp. 268-269.
- Mackinnon, I. D. R.; and Rietmeijer, F. J. M.: Bismuth in interplanetary dust. *Nature*, vol. 311, 1984, pp. 135-138.
- Mackinnon, I. D. R.; and Rietmeijer, F. J. M.: Mineralogy of chondritic interplanetary dust particles. *Reviews Geophys.*, vol. 25, 1987, pp. 1527-1553.
- Mackinnon, I. D. R.; Lindsay, C.; Bradley, J. P.; and Yatchmenoff, B.: Porosity of serially sectioned interplanetary dust particles. *Meteoritics*, vol. 22, 1987, pp. 450-451.
- Oort, J. H.: The structure of the cometary cloud surrounding the solar system and a hypothesis concerning its origin. *Bull. Astron. Inst. Netherlands*, vol. 11, 1950, pp. 91-110.
- Rietmeijer, F. J. M.: Olivines and iron-sulfides in chondritic porous aggregate U2015*B formed at low-temperature during annealing of amorphous precursor materials. *Meteoritics*, vol. 21, 1986, pp. 492-493.
- Rietmeijer, F. J. M.: Sulfides and oxides in comets. *Astrophys. J.*, vol. 331, 1988, pp. L137-L138.
- Rietmeijer, F. J. M.: Ultrafine-grained mineralogy and matrix chemistry of olivine-rich chondritic interplanetary dust particles. *Proc. 19th Lunar Planet. Sci. Conf.*, 1989, pp. 513-521.
- Rietmeijer, F. J. M.; and Mackinnon, I. D. R.: Layer silicates in a chondritic porous interplanetary dust particle. *Proc. 16th Lunar Planet. Sci. Conf.*, part 1, *J. Geophys. Res.*, vol. 90, Suppl., 1985a, pp. D149-D155.
- Rietmeijer, F. J. M.; and Mackinnon, I. D. R.: Poorly graphitized carbon as a new cosmo thermometer for primitive extraterrestrial materials. *Nature*, vol. 316, 1985b, pp. 733-736.
- Rietmeijer, F. J. M.; and Mackinnon, I. D. R.: Cometary evolution: Clues from chondritic interplanetary dust particles. *European Space Agency, SP-278* (September 1987), 1987, pp. 363-367.
- Rietmeijer, F. J. M.; Mukhin, L. M.; Fomenkova, M. N.; and Evlanov, E. N.: Layer silicate chemistry in P/Comet Halley from PUMA-2 data. *Lunar Planet. Sci.*, vol. 20, 1989, pp. 904-905.
- van der Stap, C. C. A. H.: Experimental studies of meteorites and cosmic dust, Ph.D. thesis Free University, Amsterdam, the Netherlands, 1986.
- Weissman, P. R.: The origin of comets: Implications for planetary formation. *Protostars & Planets II* (Black, D. C. and Matthews, M. S., Eds.) University of Arizona Press, Tucson, 1985, pp. 895-919.

(*) This work was supported by NASA Grant NAG 9-160.